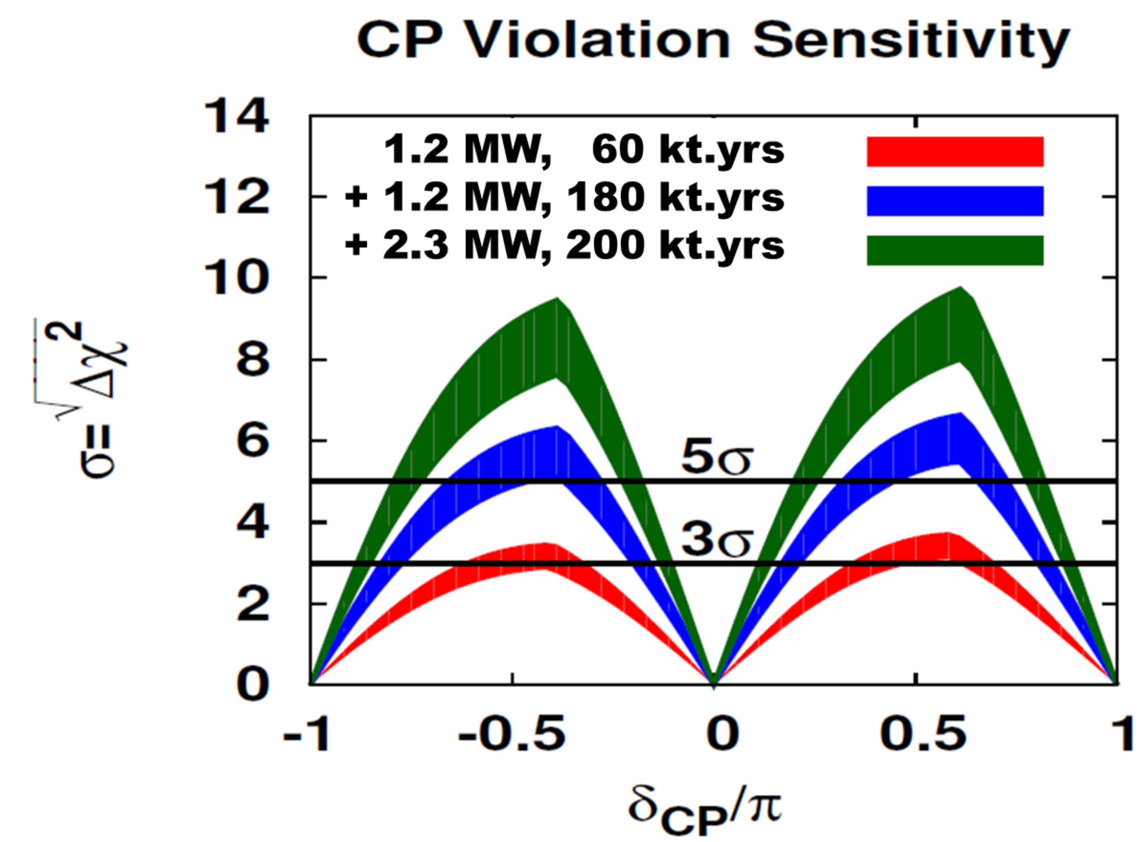
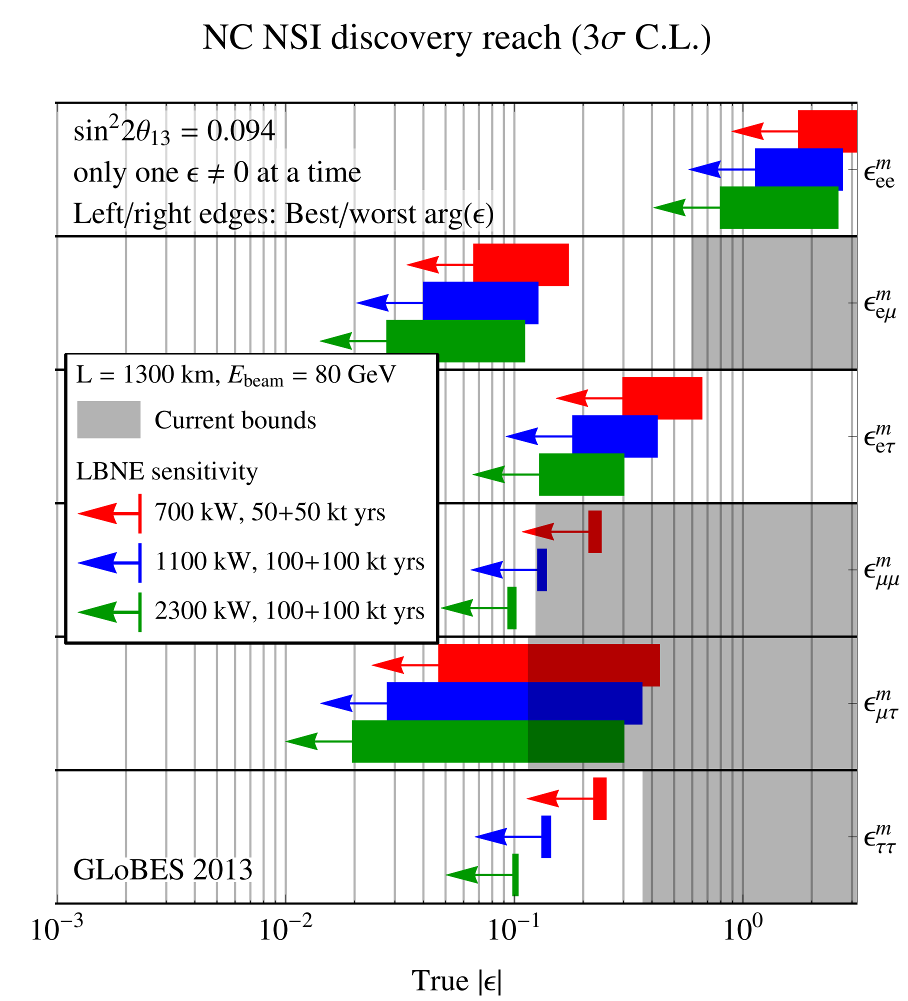
Overview of Physics with High Intensity Proton Beams

Andreas S. Kronfeld
December 16, 2013
P5 Meeting @ BNL

Core Program with High-Intensity Proton Beams

- Fermilab accelerators include the Main Injector and the Booster, being souped up in the Proton Improvement Plan (PIP):
  - 700 kW for 120 GeV MI, i.e., NOνA;
  - 20 kW for 8-GeV Booster, i.e., Mu2e, New Muon *g*–2.
- At the November 3rd Town Hall meeting, Fermilab recommended
  - muon physics: Mu2e and New Muon *g*–2;
  - neutrino physics: LBNE and short baseline ν experiments.
- PIP-II: 1200 kW to LBNE and 40 kW to extended 8-GeV program.





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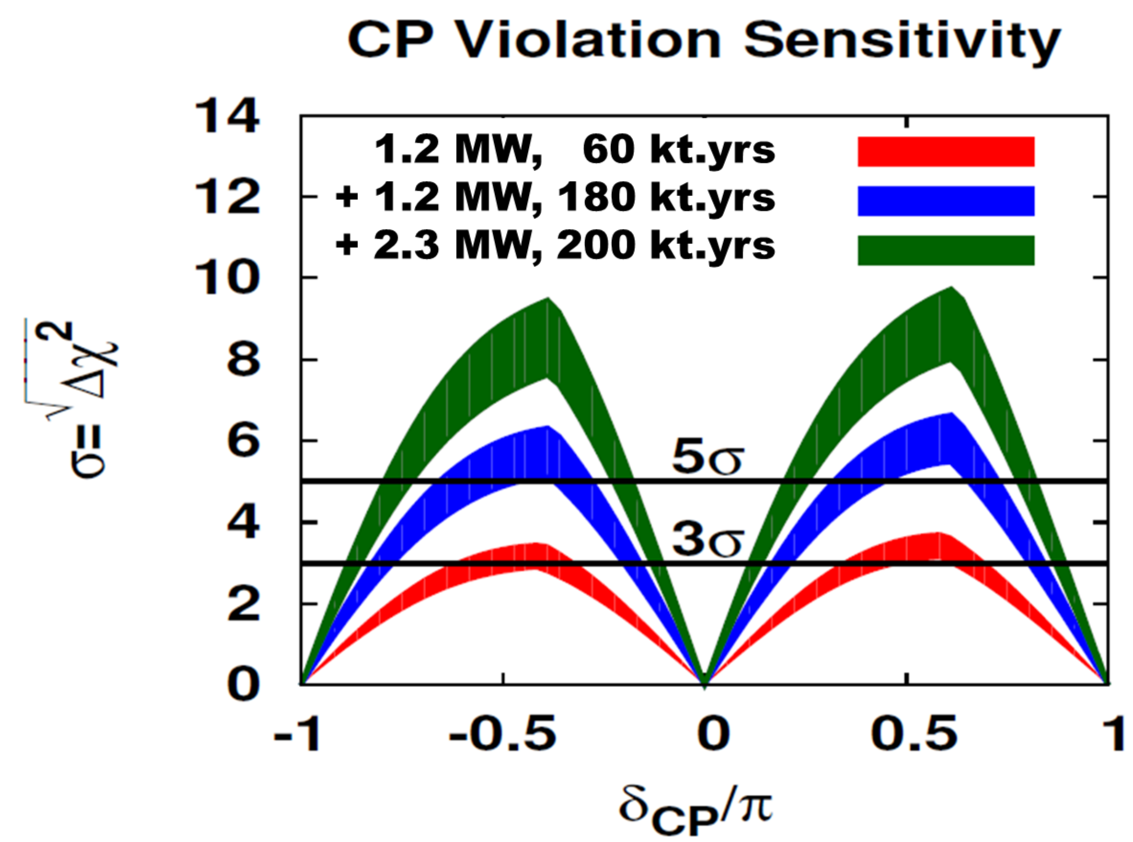
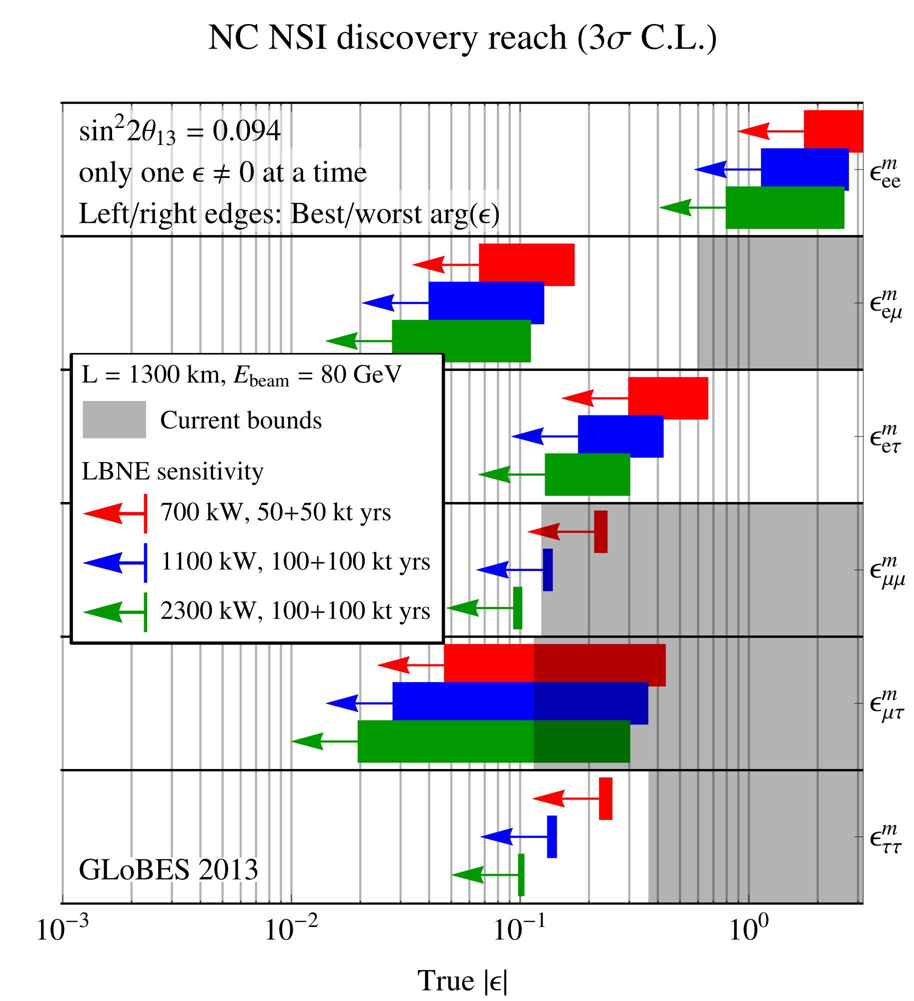
PIP

&

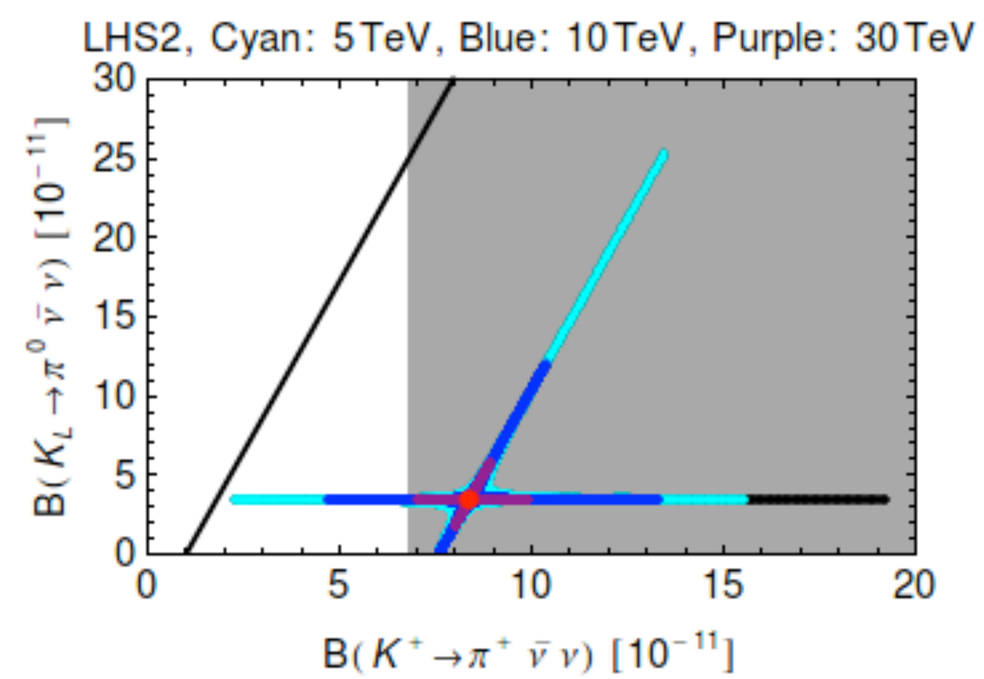
PIP-II





Future Possibilities with High-Intensity Proton Beams

- Proposed MI experiments (slot for operations between NOvA and LBNE):
  - ORKA studies rare kaon decays, esp. $K^+ \to \pi^+ \nu \bar{\nu}$;
  - νSTORM studies sterile neutrinos ⇐ hints from data;



- With higher-duty factor in PIP-II, Mu2e-II could explore signal.
- CW upgrade to PIP-II could enable experiments with a spallation target:
  - NNbarX searches for neutron-antineutron oscillations, testing post-EWPT baryogenesis;
  - searches for neutron & atomic electric dipole moments, exploring BSM *CP* violation.
- PIP-II is platform for further upgrades: LBNE@2MW, neutrino factories, $\mu^+\mu^-$ collider, VLHC.

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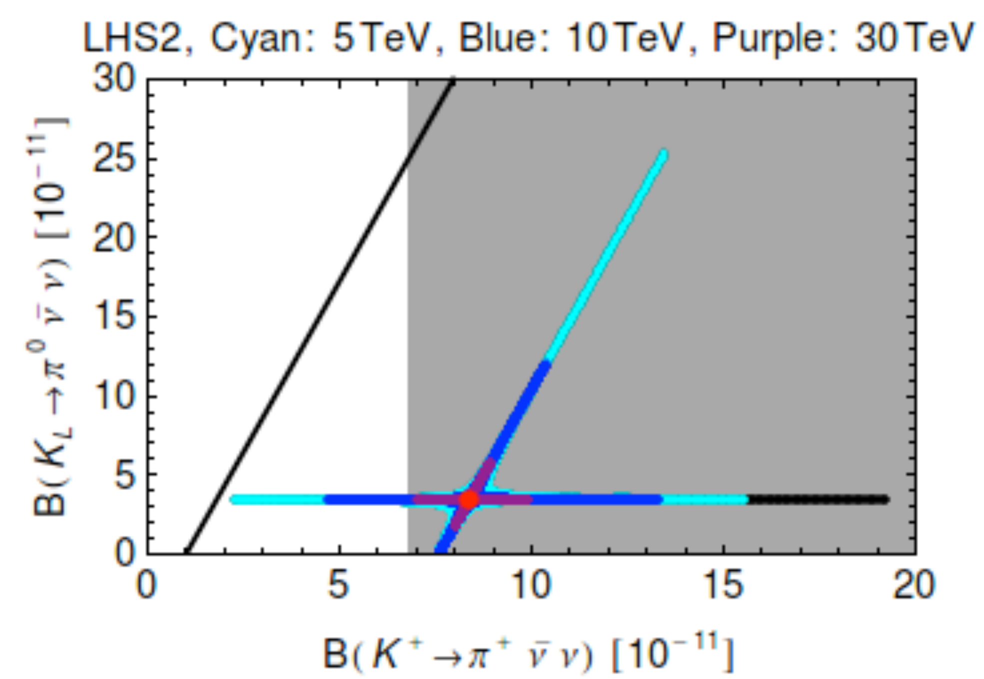
beautiful ideas



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modest PIP-II extension

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Lagrangian Will Keep Us Together

- The aim of particle physics (at any "frontier") is to understand
  - $\mathscr{L} = \mathscr{L}_{\mathsf{SM}} + \mathscr{L}_{\nu\mathsf{M\&M}} + \mathscr{L}_{\mathsf{BSM}} + \mathscr{L}_{\mathsf{QG}}$
- In experiments below few GeV, "integrate out" heavy BSM fields
  - $\mathscr{L} = \mathscr{L}_{\mathsf{SM}} + \mathscr{L}_{\nu\mathsf{M\&M}} + \sum_{\mathscr{O}} \sqrt{2} G_F \mathscr{G}_{\mathscr{O}} \mathscr{O}$
- Over 1000 operators $\mathscr{O}$ (hence lots of experiments). Most of this talk will concern:
  - $\mathscr{L}_{\nu\mathsf{M\&M}}$, $\dfrac{P_{ij}}{\Lambda^2}\bar{\ell}_i\sigma_{\mu\nu}\ell_j F^{\mu\nu}(m_i+m_j)$, $\dfrac{T^A_{ijkl}}{\Lambda^2}\bar{\ell}_i\Gamma^A\ell_j\bar{\psi}_k\Gamma^A\psi_l$, $\dfrac{U^A_{ijkl}}{\Lambda^2}\bar{\ell}_i\Gamma^A\nu_j\bar{\psi}_k\Gamma^A\psi_l$, $\mathscr{L}_{\mathsf{CPV}}$

  and their overlap and interplay.
- The scale of BSM physics is Λ; the dynamics & texture of that scale is encoded in P, T, U.

Kenneth Wilson
1936-2013
"Wilson coefficients"

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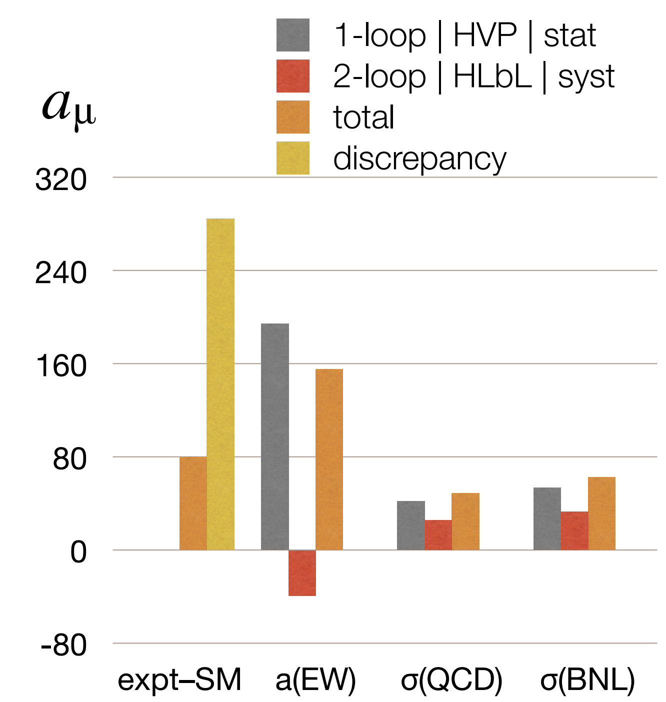
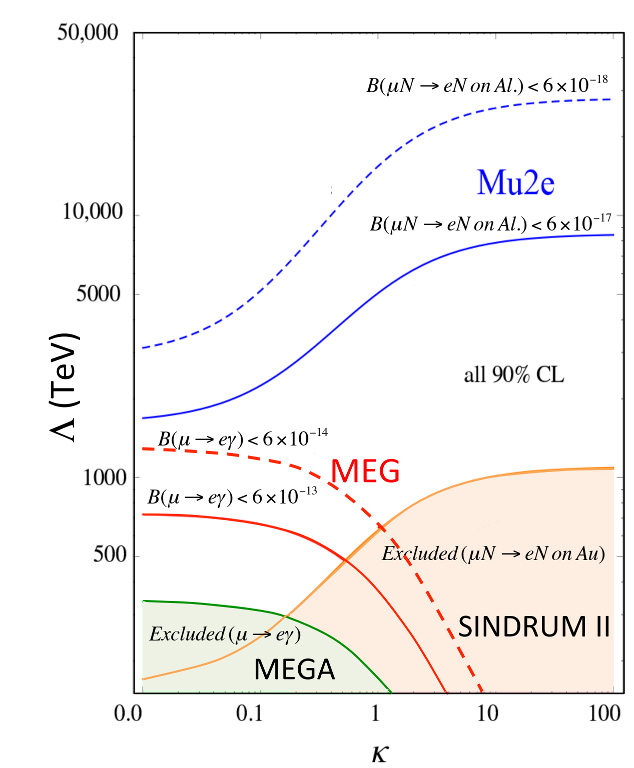
Connection between Neutrino and Muon Physics



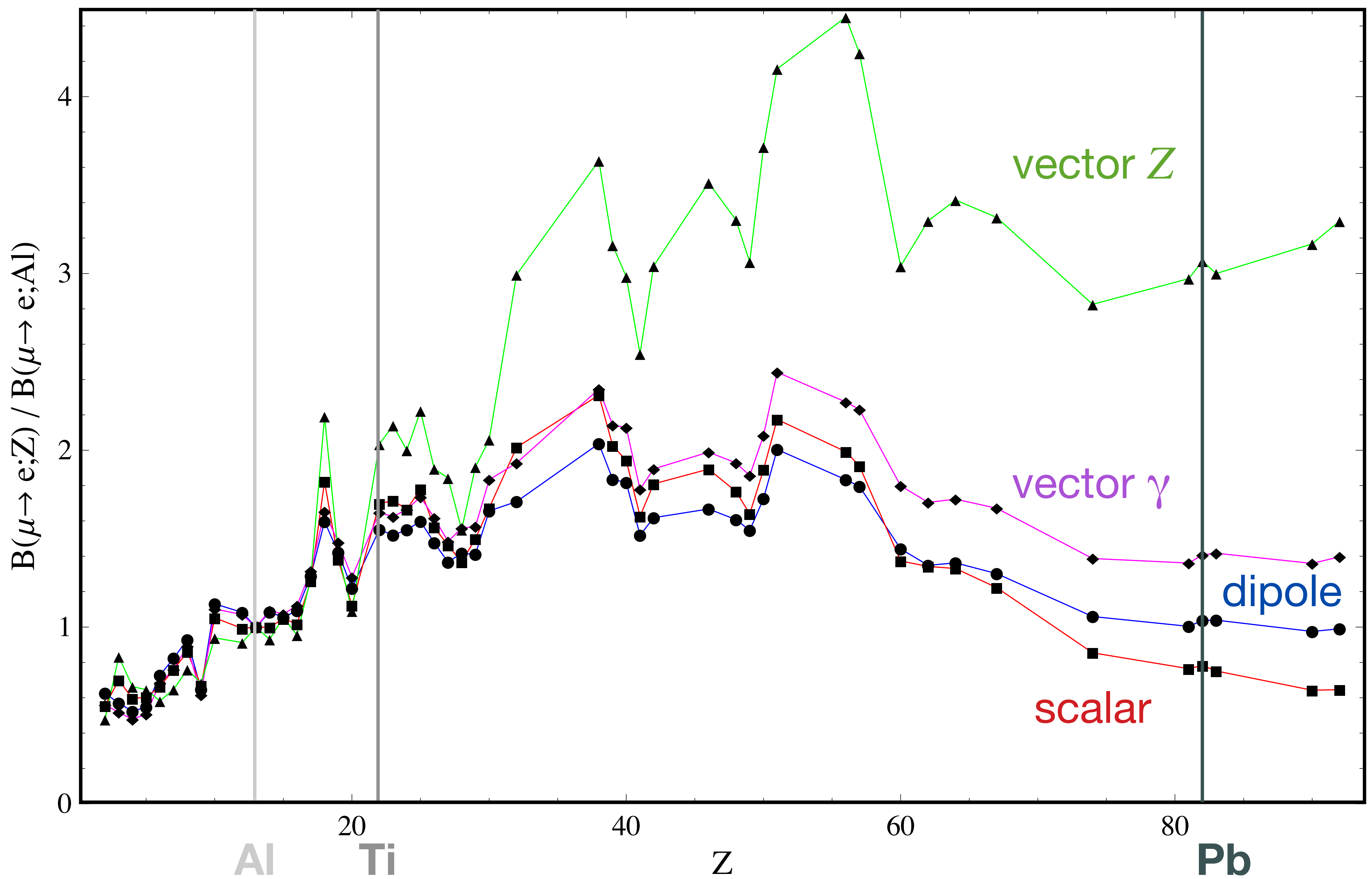
- New Muon g–2 tests huge & durable ~3.5σ difference with SM:
  - 1.6 times the W & Z contributions—room for new physics, say W' & Z'.
- Neutrino mass and mixing implies charged lepton number is not conserved; Mu2e improves BR÷10[4], pushing the scale probed to $\Lambda \approx 10^4$ TeV:
  - models of ν mixing, *e.g.*, susy seesaw, predict discovery at Mu2e;
  - Mu2e can also detect $\mu^-\ {}^{27}\mathrm{Al} \to e^+\ {}^{27}\mathrm{Na}$—analog to ββ0ν.
- LBNE studies 3-neutrino paradigm—tied to charged leptons—especially:
  - *CP* violation ⇒ leptogenesis ⇒ baryogenesis;
  - non-Standard (Z') interactions.



Mu2e-II: Explore Signal or Increase Sensitivity

Knoepfel *et al.*, arXiv:1307.1168

- PIP-II high-duty-factor option increases power to muon campus × 10.
- Runs on many target nuclei disentangle CLFV interaction [hep-ph/0203110]:



- Choose optimal bunch spacing for each nucleus:

- With PIP-II 800 MeV protons: no antiproton background.

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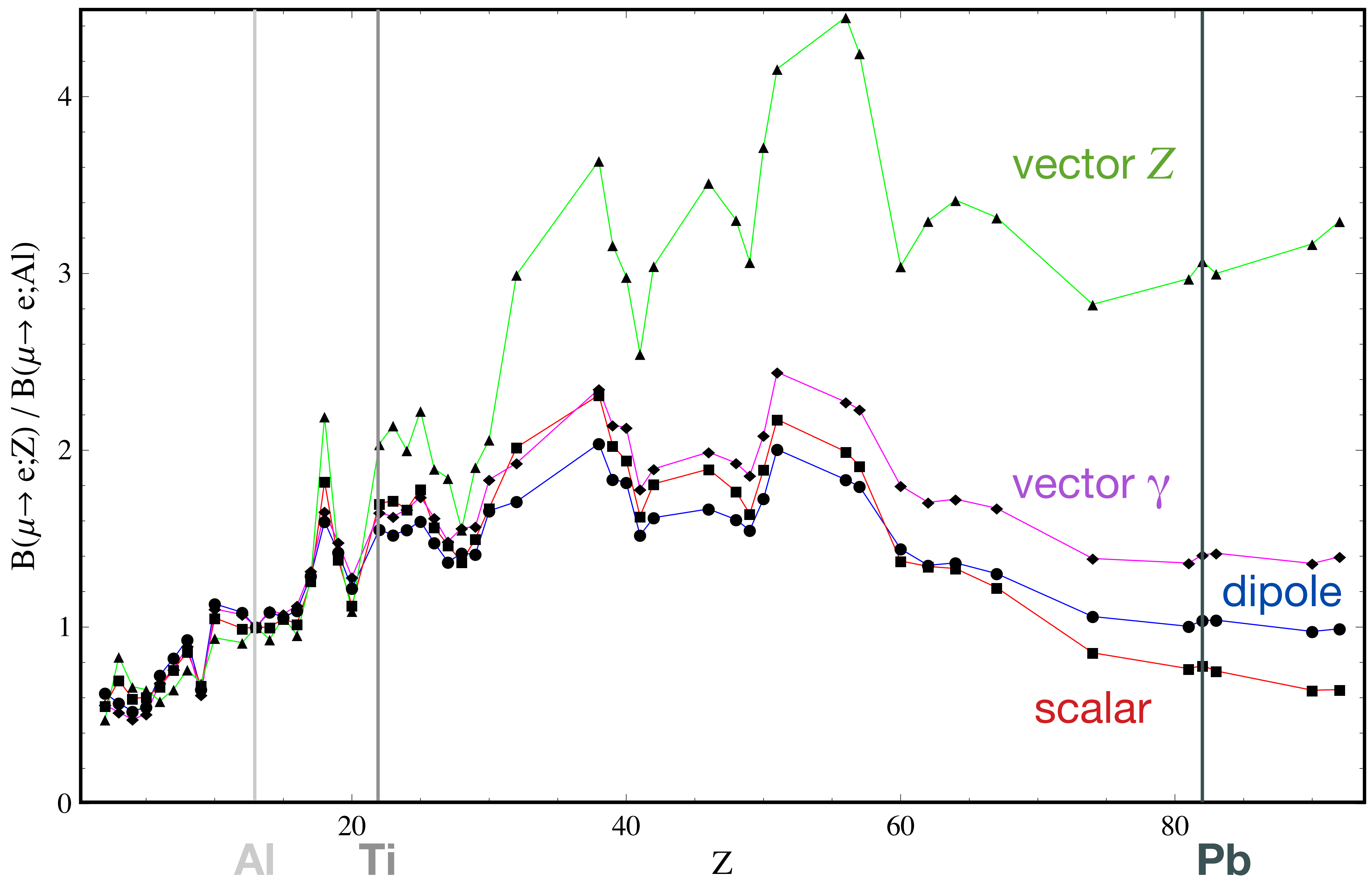

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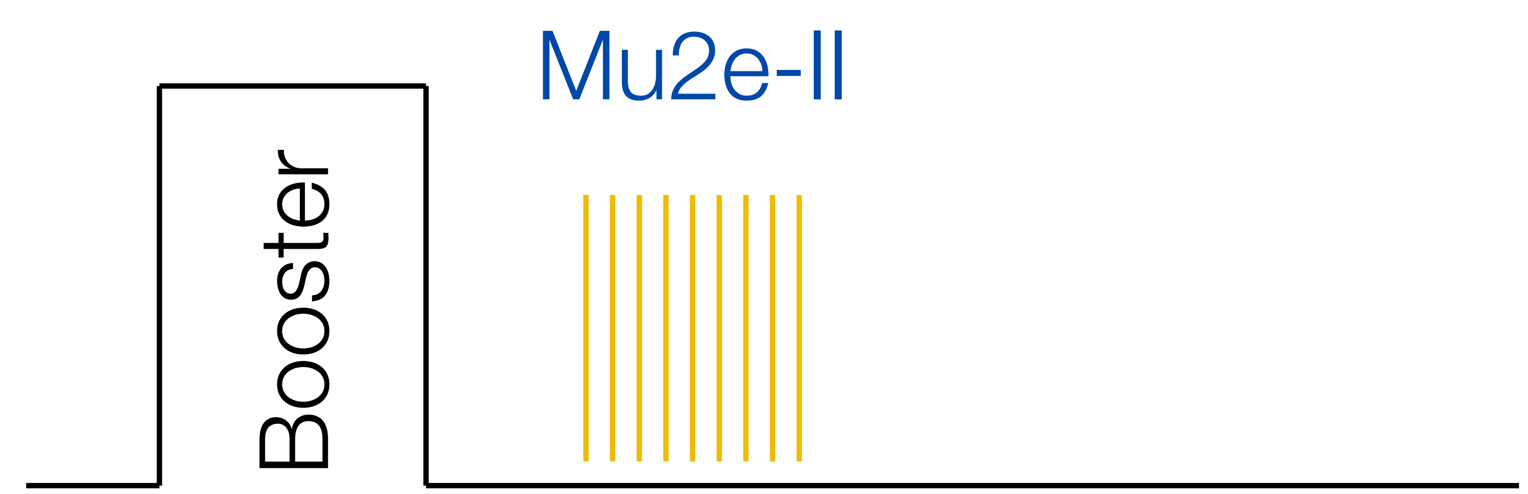

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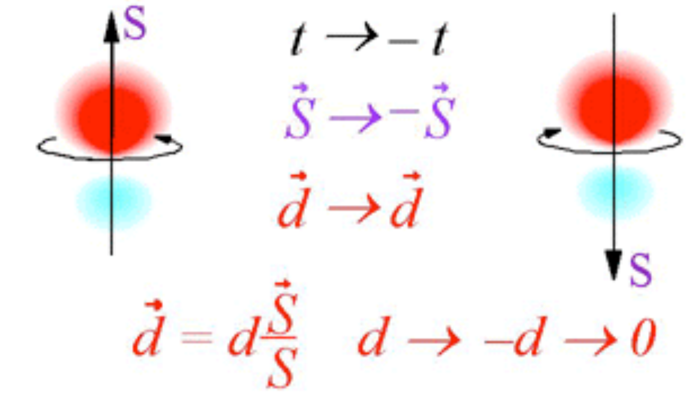
Electric Dipole Moments

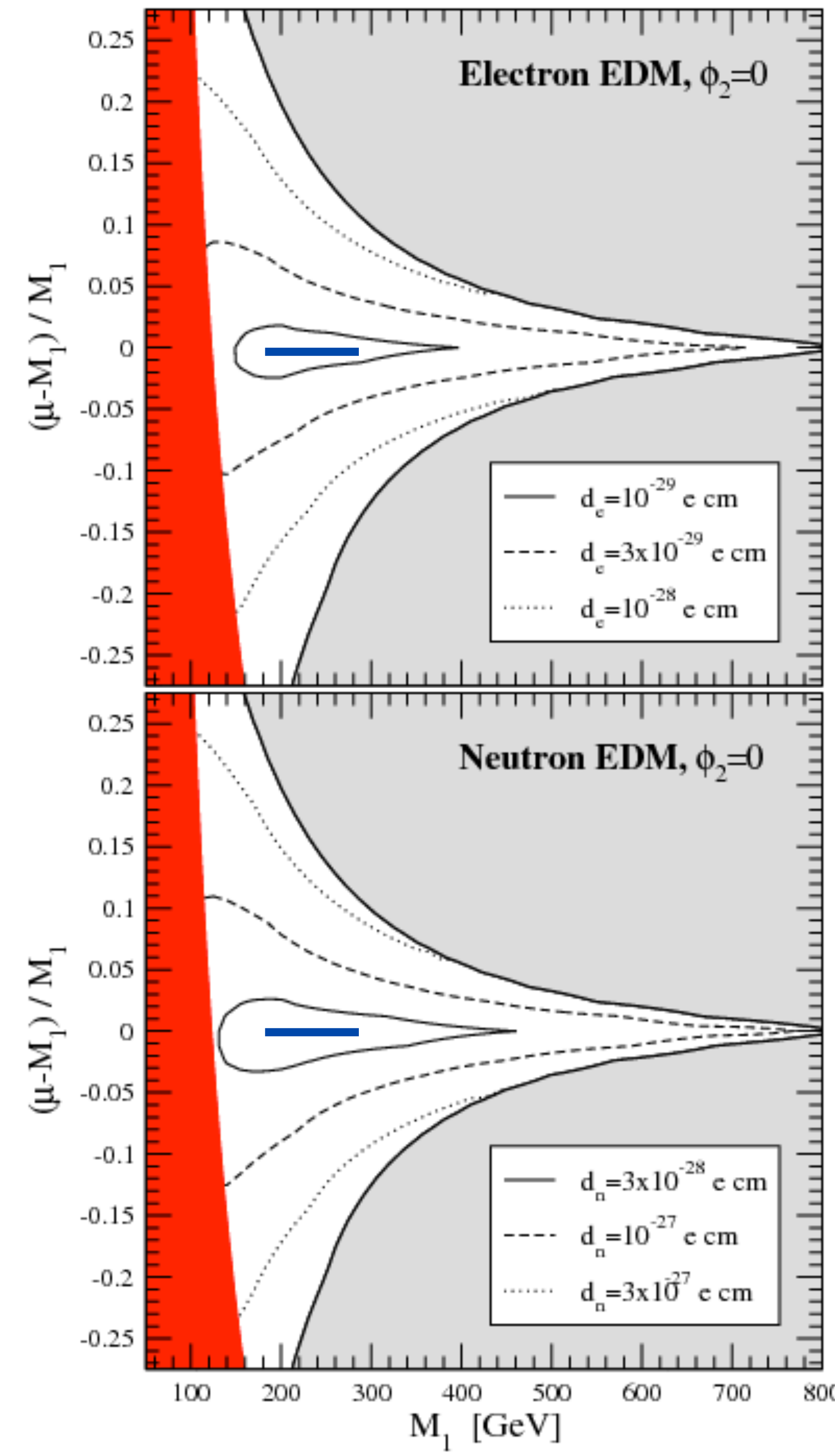


- The electric dipole moment couples spin to electric fields:
  - *T* odd, so, in a *CPT*-invariant world, a signal of new *CP* violation (as needed for BAU).
- A CW upgrade to PIP-II would enable experiments with muons, neutrons, and certain atoms (⇐ quark & electron EDMs). Polarized beam (235 MeV KE) would enable Proton SR EDM.
- CPV from θ term in QCD, phase of CKM matrix, phase(s) of PMNS matrix, BSM/Higgs:
  - neutron: $-\sin\theta + \text{GIM}\times\text{loop}\times\sin\delta_{KM}$ + BSM < $3\times10^{-26} \to 10^{-29}$ (from PX Stage 1 study);
  - proton: $+\sin\theta + \text{GIM}\times\text{loop}\times\sin\delta_{KM}$ + BSM < $7\times10^{-23} \to 10^{-29}$ (from PX Stage 1 study).
- Atomic & neutron EDMs would share spallation target with NNbarX.

The
Nima
Talk

Complementarity with Colliders

- EDMs are very sensitive to *CP* violation in the Higgs sector.
- The parameter space of the MSSM that explains the baryon asymmetry predicts electron and neutron EDMs that exceed certain values (figure).
- PX Stage 1 (≈ PIP-II CW) limits (10^{-30} for *e*; 10^{-29} for *n*) would shrink the allowed region almost to nil.
- References: hep-ph/0606298, arXiv:0910.4589 [hep-ph], arXiv:1003.2447 [hep-ph], arXiv:1206.2942 [hep-ph].
- In figures: bino mass M_1; Higgs-higgsino parameter μ; LEP susy exclusion; not enough baryons.



V. Cirigliano et al. [arXiv:0910.4589]

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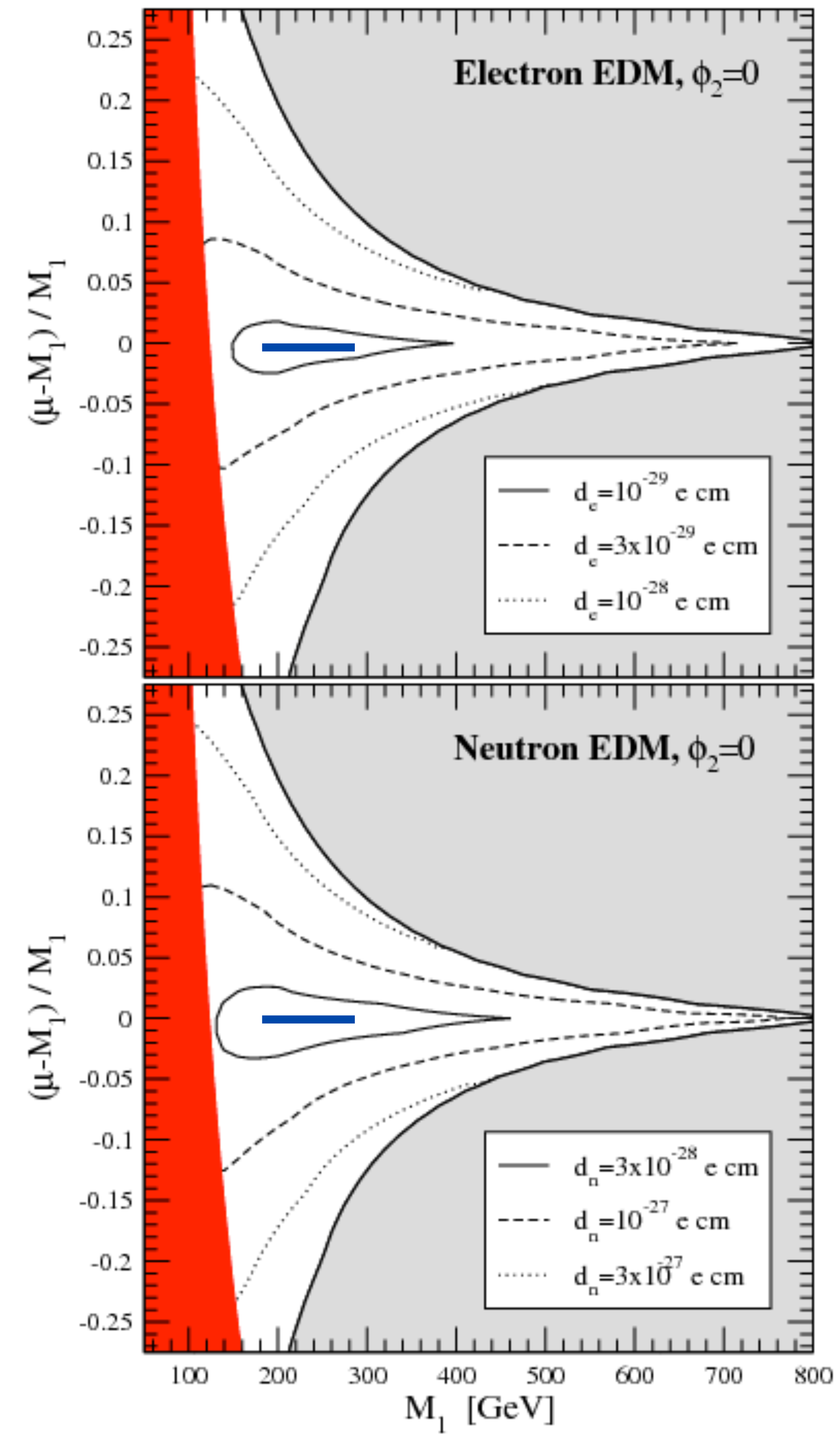
Opportunity to collaborate with AMO & NP physicists (Callan, Kachru)



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Summary

- New Muon g–2, Mu2e, and LBNE anchor vibrant US program in accelerator-based HEP …
  - … providing a three-pronged attack on lepton-flavor interactions …
  - … advancing our understanding of flavor, *CP* violation, baryon violation …
  - … offering clues to new forces between the TeV and QG scales.
- This program (and any expansion) requires a powerful, flexible accelerator that can drive many simultaneous experiments, probing FCNC (and all that entails), *CP*V, $\not{B}$, etc.
  - … providing a platform to future ambitions: neutrino factory, muon collider, or VLHC.
- (Personal interest: lattice QCD will enhance all these experiments.)

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Elegant and essential
complement
to LHC!

Useful References

- New Muon g–2: Annu. Rev. Nucl. Part. Sci. 62 (2012) 237 [doi], arXiv:1311.2198.
- Mu2e: arXiv:1303.4097 (theory), arXiv:1307.5787 (expt), arXiv:1307.1168 (Mu2e-II).
- LBNE: arXiv:1307.7335.
- Other and all topics: arXiv:1306.5009.

Backup Slides

Discoveries from rare processes and precision physics

- Discovery of the electroweak scale: $2^{1/2}G_F = g^2/M_W^2 = v^{-2} = (246\ \mathrm{GeV})^{-2}$.
- Flavor physics: muon, strangeness, 2nd neutrino, 3rd generation. Who ordered that?
- Neutrinos are massless.
- *CP* violation.
- Charged currents of all kinds; high suppression of FCNC.
- Hints of (or evidence for) charm, weak bosons, top, & Higgs—before real detection feasible.
- Neutrinos are not massless after all.

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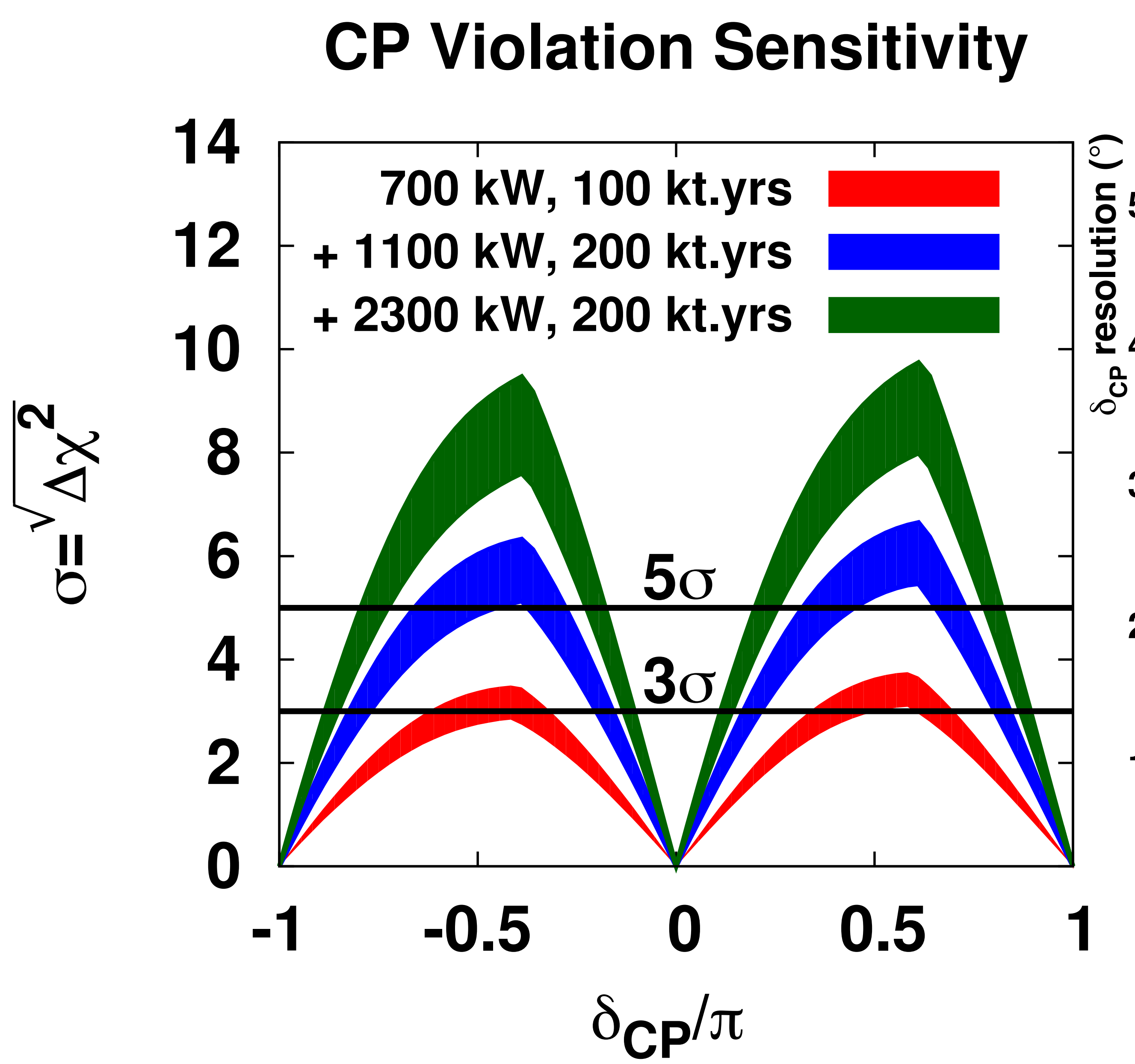
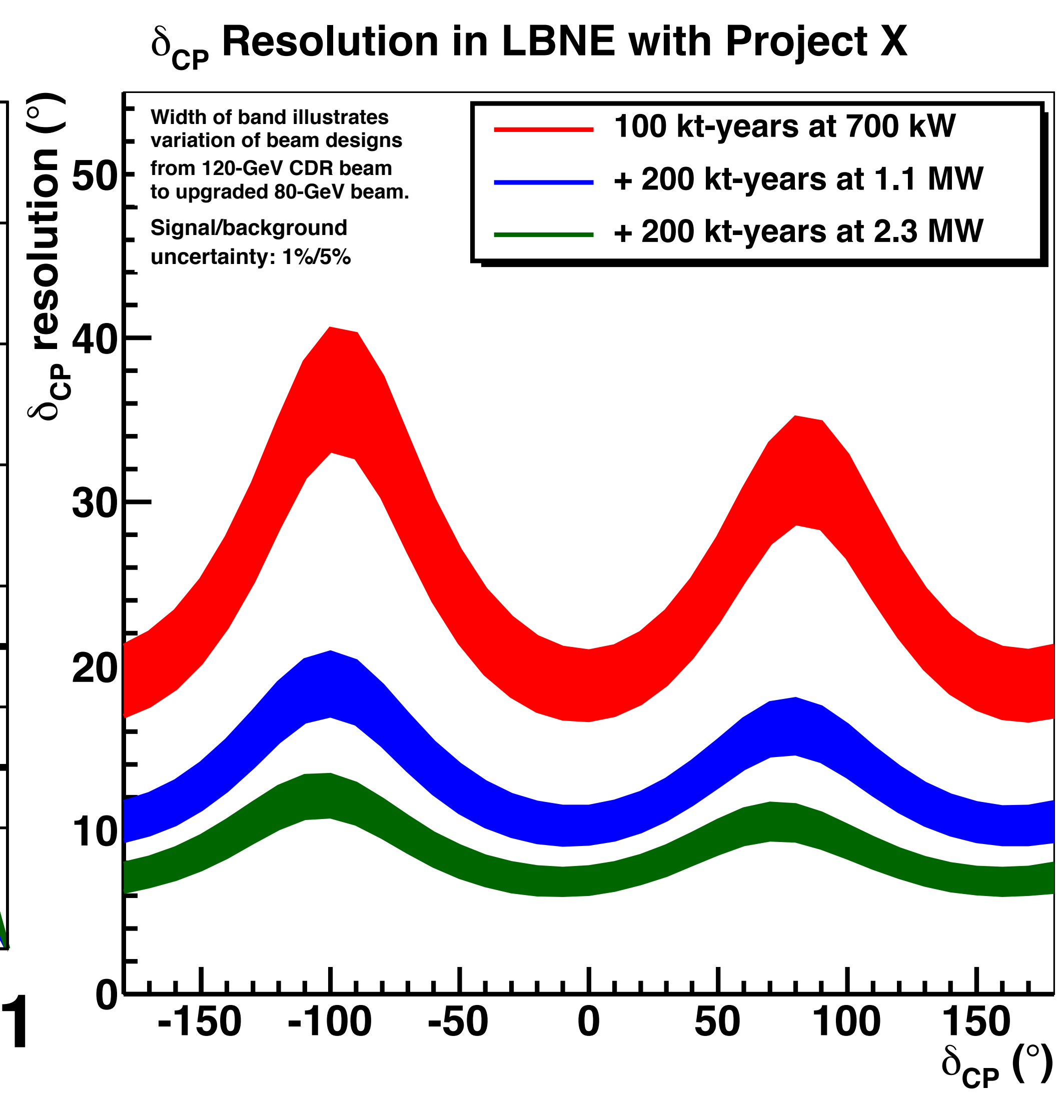
LBNE and *CP* Violation

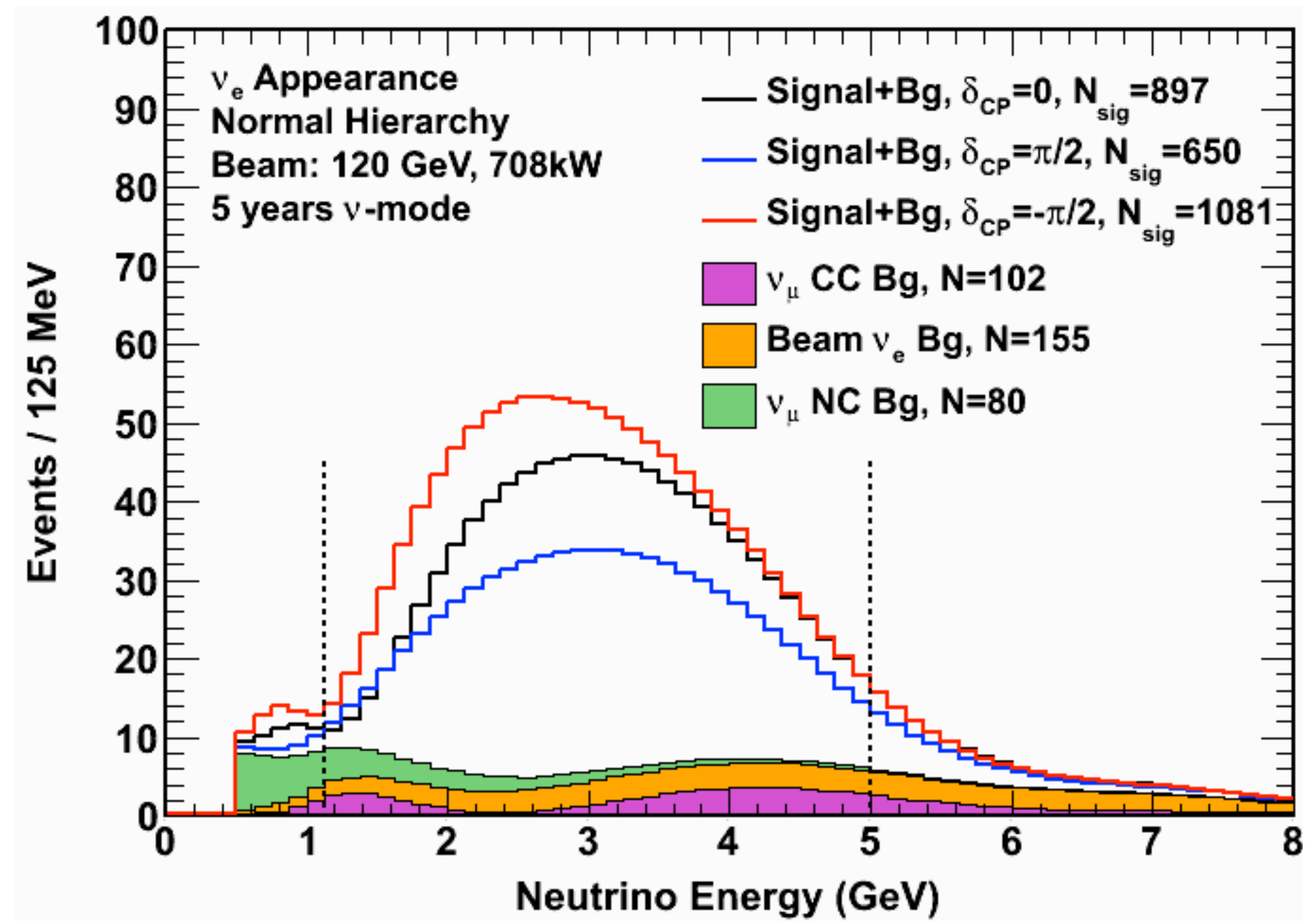
arXiv:1307.7335

- LBNE's sensitivity to *CP* violation improves with PIP-II's × 1.6 power.
- With higher power, LBNE will profit from flexible energy choice of neutrino beam:





Z. Isvan (BNL)



- For latest global fits of PMNS matrix, see arXiv:1312.2878.

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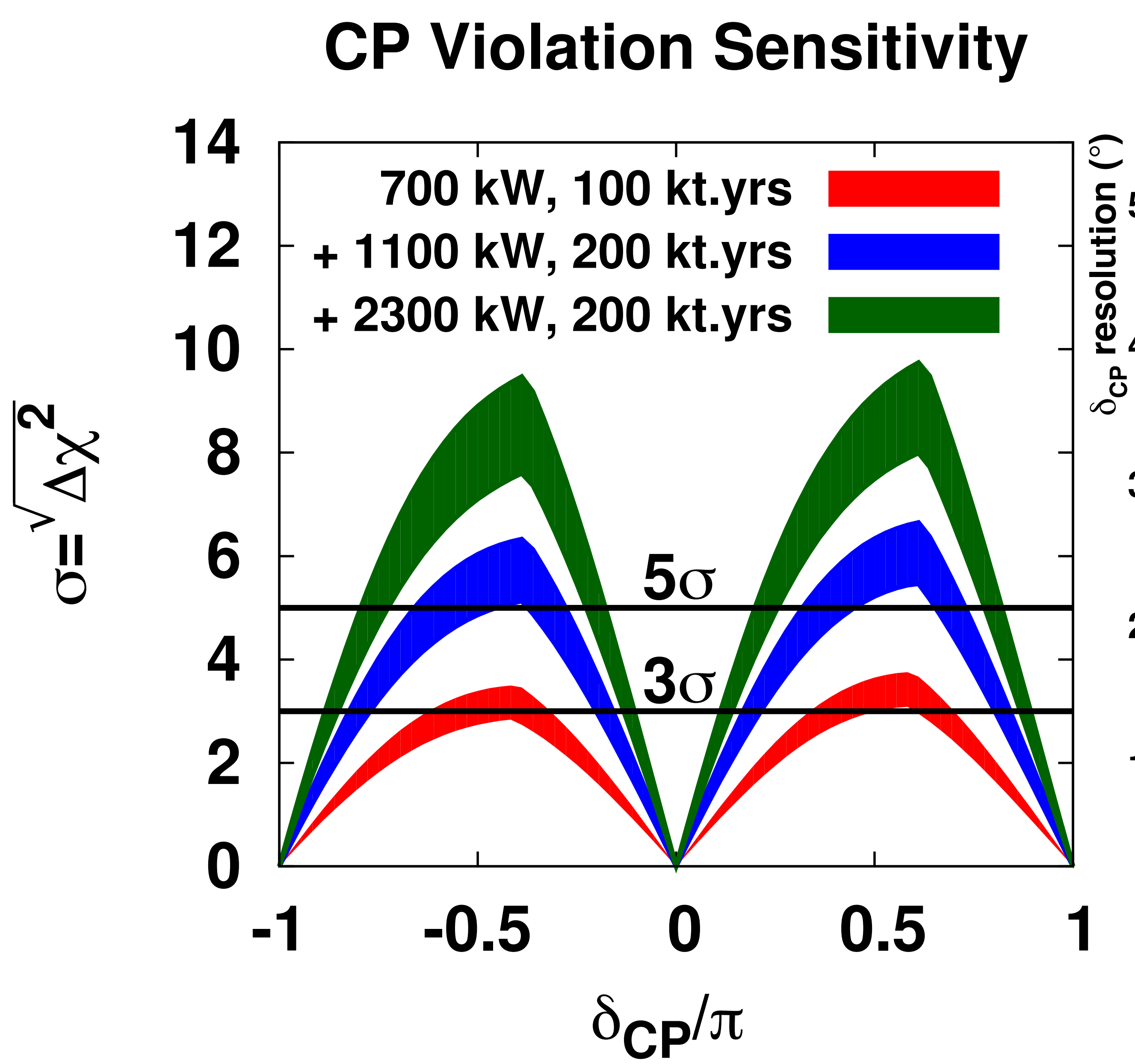

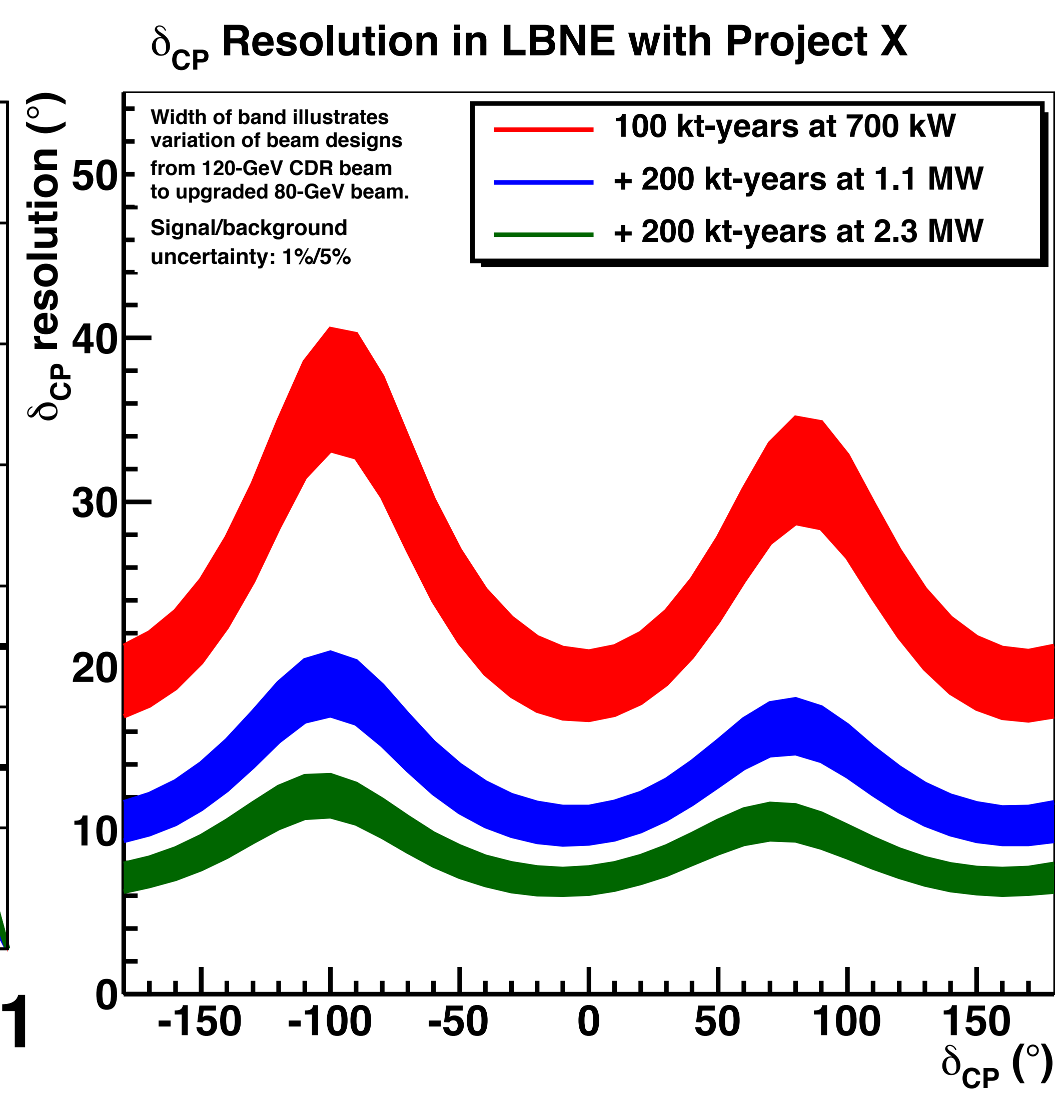

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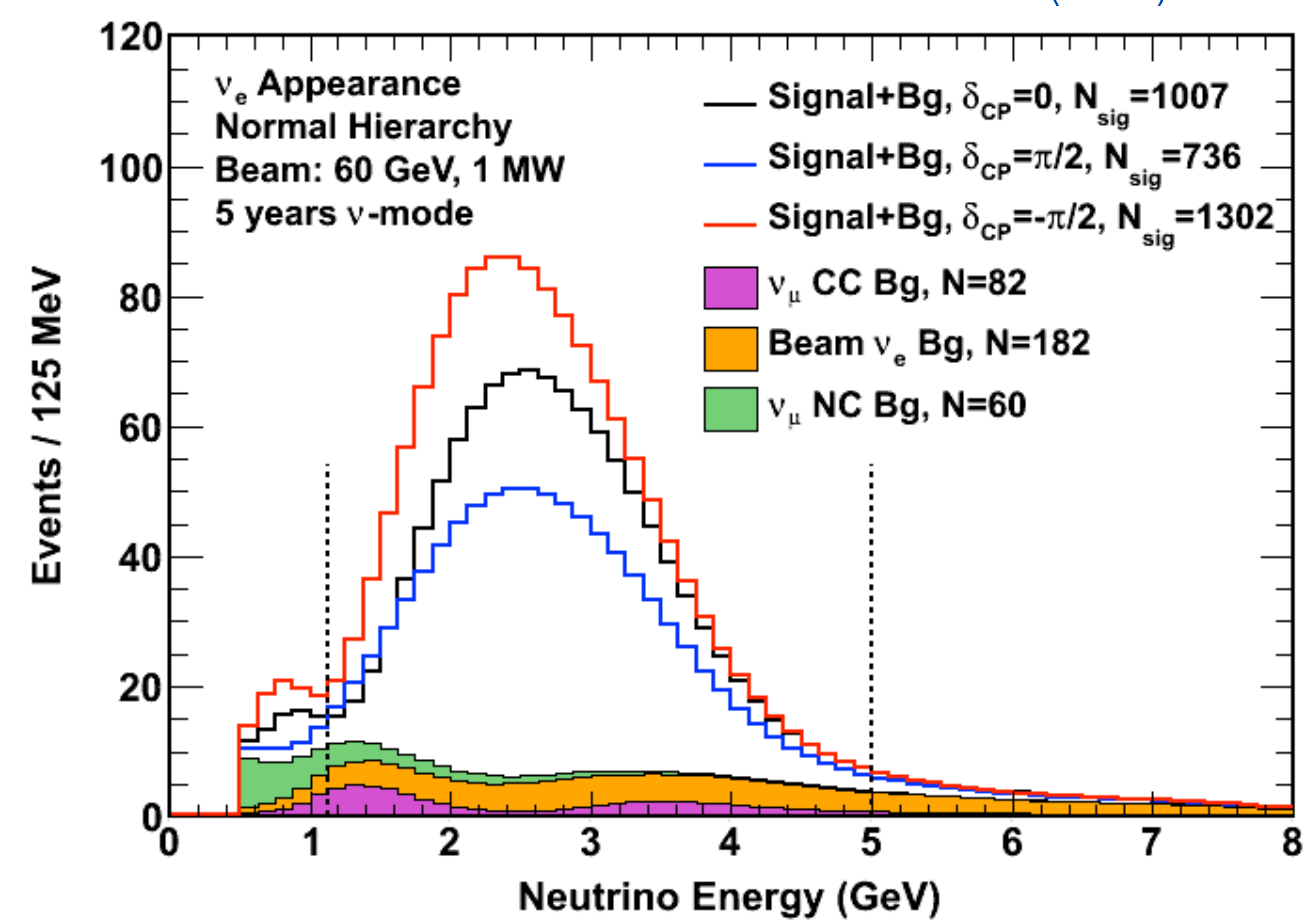

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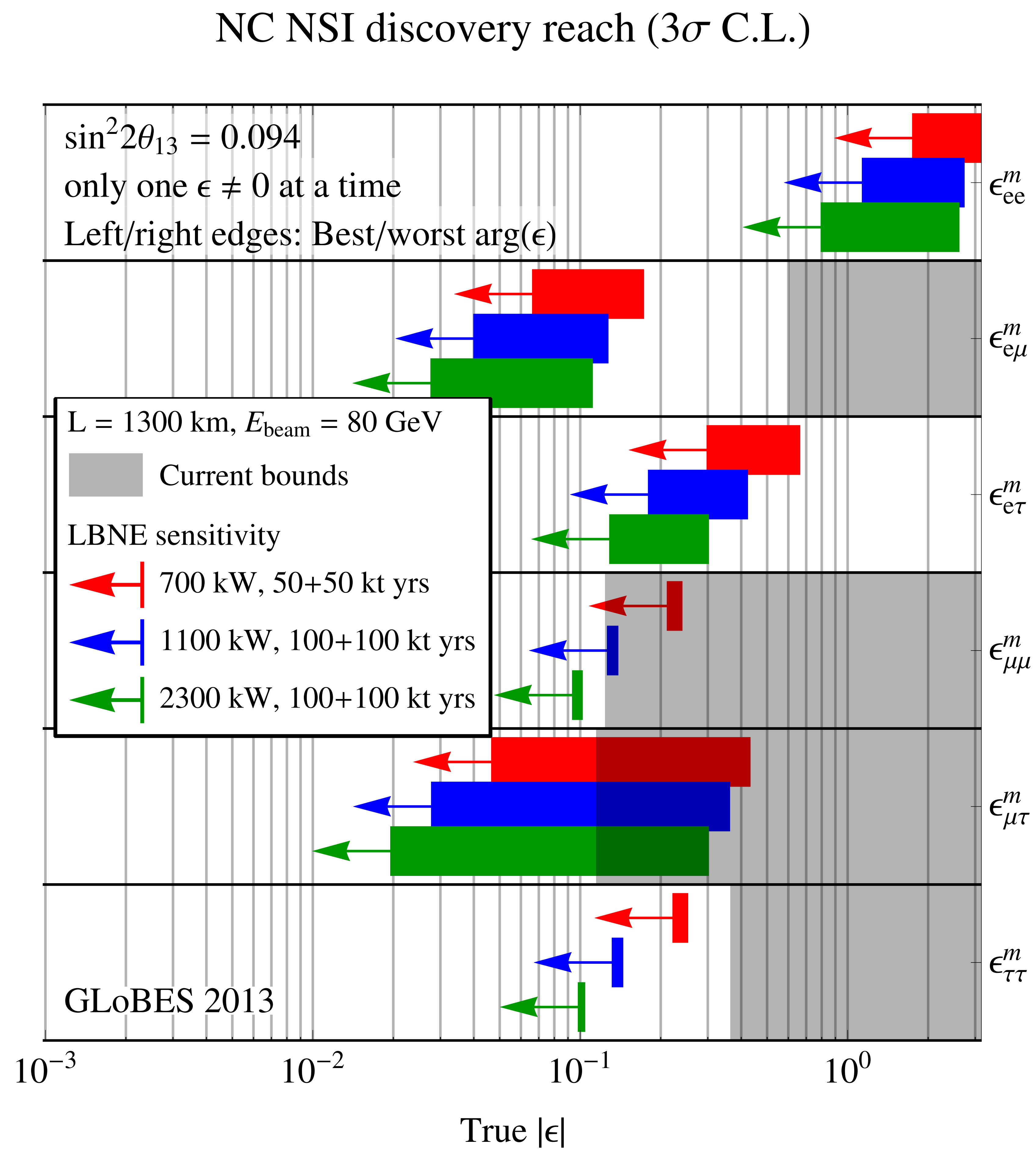
Non-Standard Neutrino Interactions

- If neutrinos interact w/ matter via non-Standard interactions (e.g., Z'), their propagation becomes:

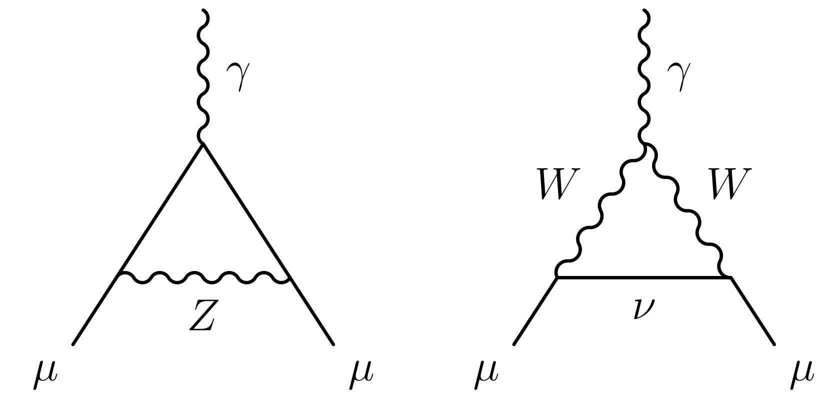
$$H = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger + \tilde{V}_{\mathrm{MSW}}$$

$$\frac{\tilde{V}_{\mathrm{MSW}}}{\sqrt{2} G_F} = N_e \begin{pmatrix} 1+\varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} \end{pmatrix} \text{“} = G_{\mathscr{O}} \text{”}$$

- Distortions in ν_μ disappearance could be sign of mixing with Kaluza-Klein neutrinos.

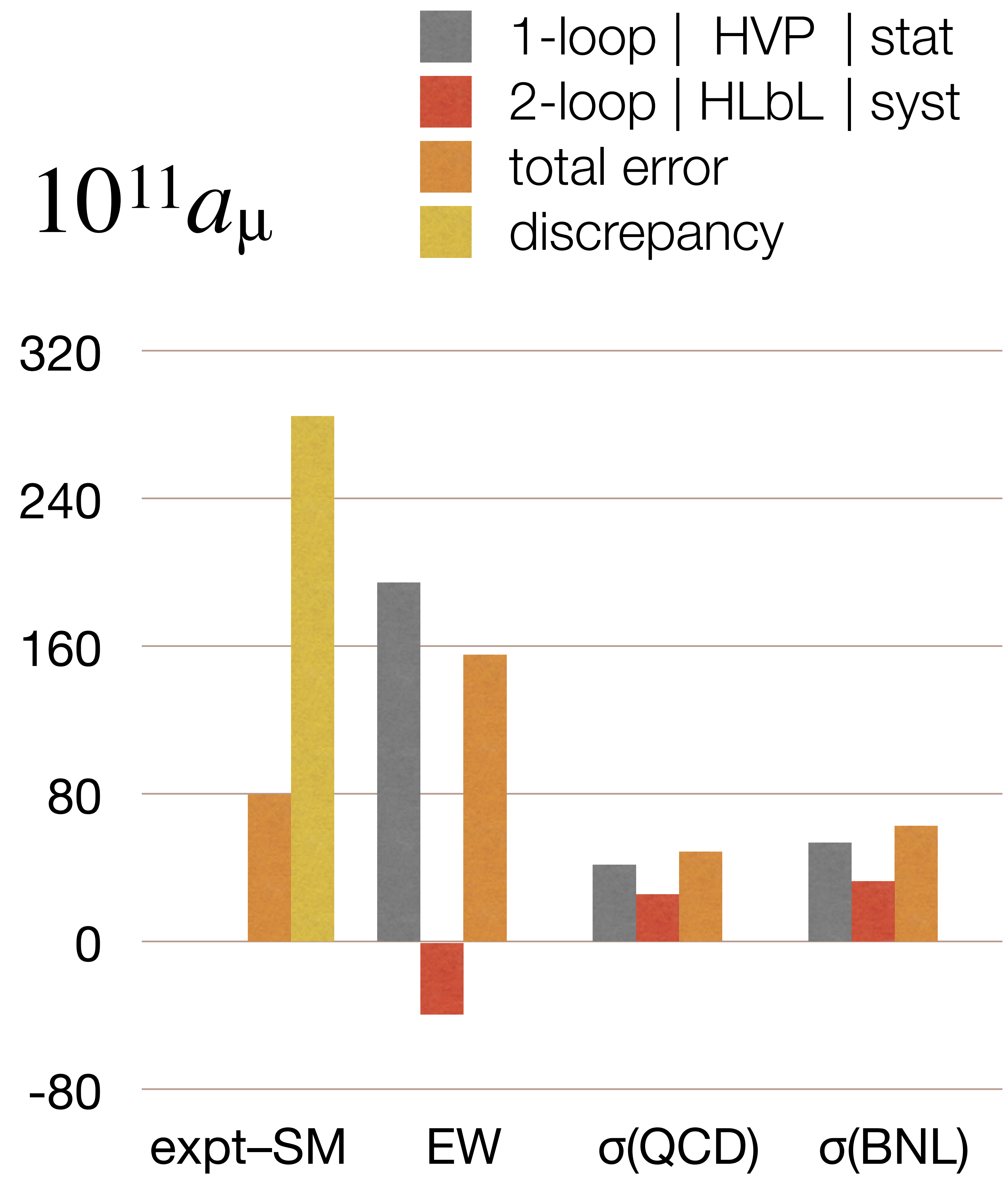


Discrepancy in Muon g–2



arXiv:1012.0055

- It is huge, about 1.8×EW (1&2)-loop contributions.
- Lots of room for 1σ movements and new physics.
- Discrepancy is such that BNL821 > SM …
    - … maybe less significant with τ decay for HVP.
- New Muon g–2 will cut expt uncertainty by ÷4.
- On time-scale of New Muon g–2, lattice QCD should reduce theory error by ÷4:
    - HVP is likely; HLbL *necessary*.



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Basic Physics of Mu2e

- Neutrino mixing implies $\mu \to e \neq 0$ but $\sim 10^{-54}$.

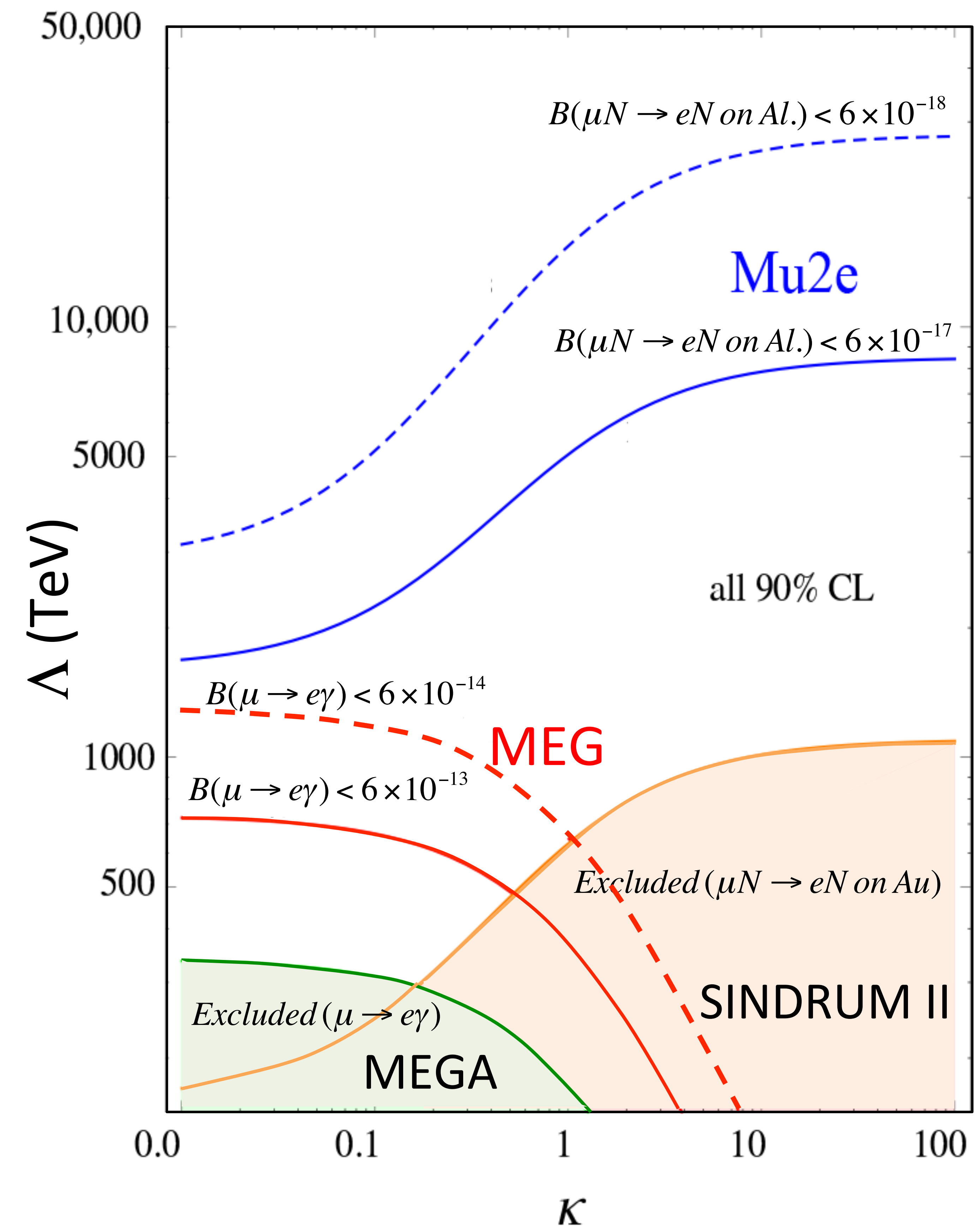
- Examines operators

$$\frac{P_{e\mu} m_\mu}{\Lambda^2} \bar{e}\sigma_{\mu\nu}\mu F^{\mu\nu} + \frac{T^A_{e\mu kk}}{\Lambda^2} \bar{e}\Gamma^A \mu \bar{q}_k \Gamma^A q_k$$

with $P = (1+\kappa)^{-1}$, $T^{\gamma_\mu} = \kappa(1+\kappa)^{-1}$ in the plot.

- Target $R(\mu\,^{27}\mathrm{Al} \to e\,^{27}\mathrm{Al}) \sim 6\times10^{-17}$, shown as the solid blue line in the plot, excludes up 10^4 TeV.

- Complete BSM models that aim to improve SM predict discoverable signal.



adapted from arXiv:1303.4097

Reach for Z' with $K \to \pi\nu\nu$

Buras, De Fazio, Girrbach, arXiv:1211.1896

- SM is red dot; boomerangs are various Z' models. Black line is GN bound; black regions excluded by $K \to \mu\mu$.
- BNL expt reached 1-5 TeV.
- The reach with ~100 events is ~10 TeV.
- The reach with ~3000 events is ~30 TeV.
- The boomerang shapes arise because the neutral mode picks out only the imaginary part of the Wilson coefficient.
  - As $M_{Z'} \to \infty$, the boomerangs come closer and closer to the SM.

7 An Excursion through Z' Scenarios 45

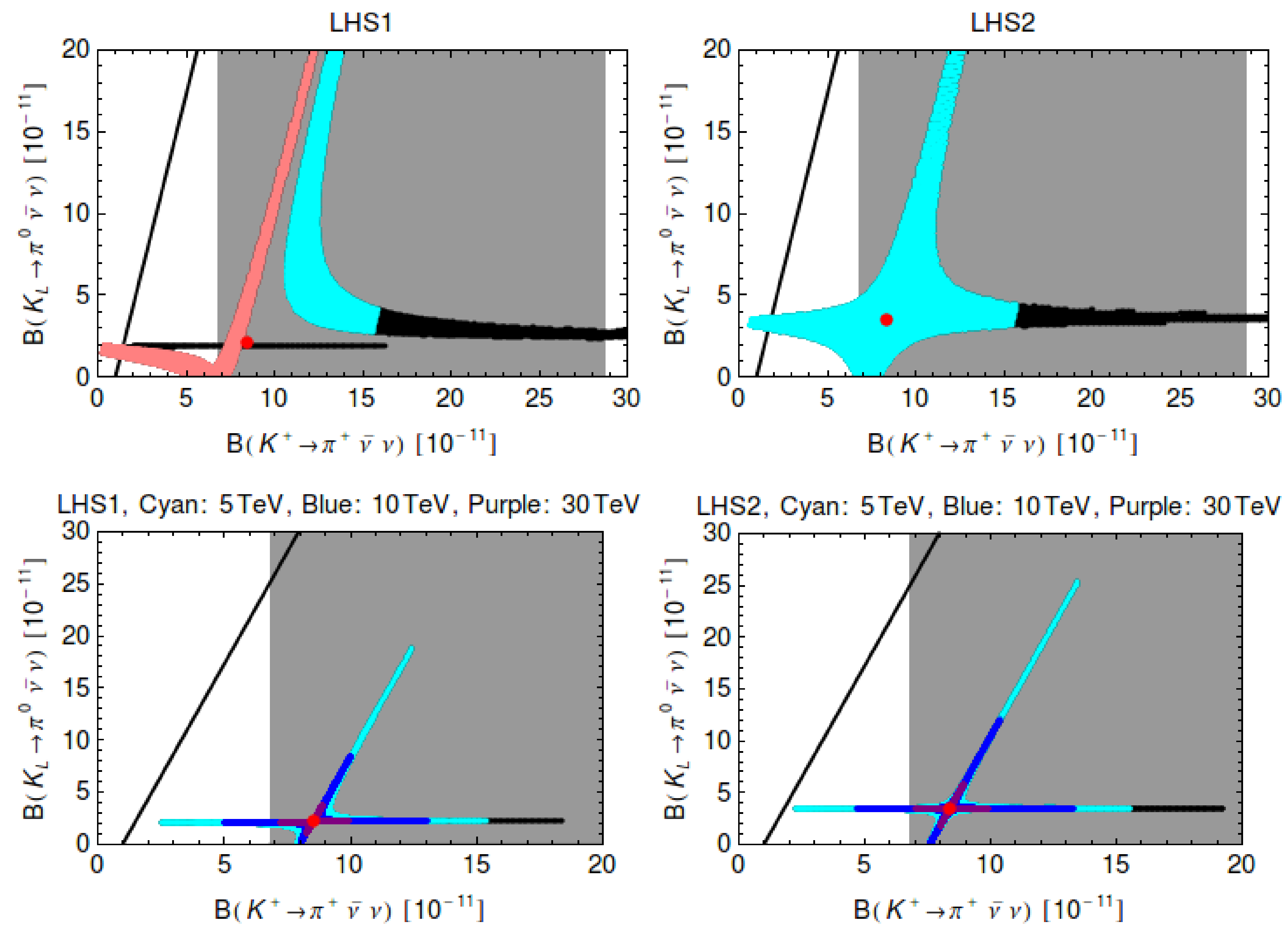
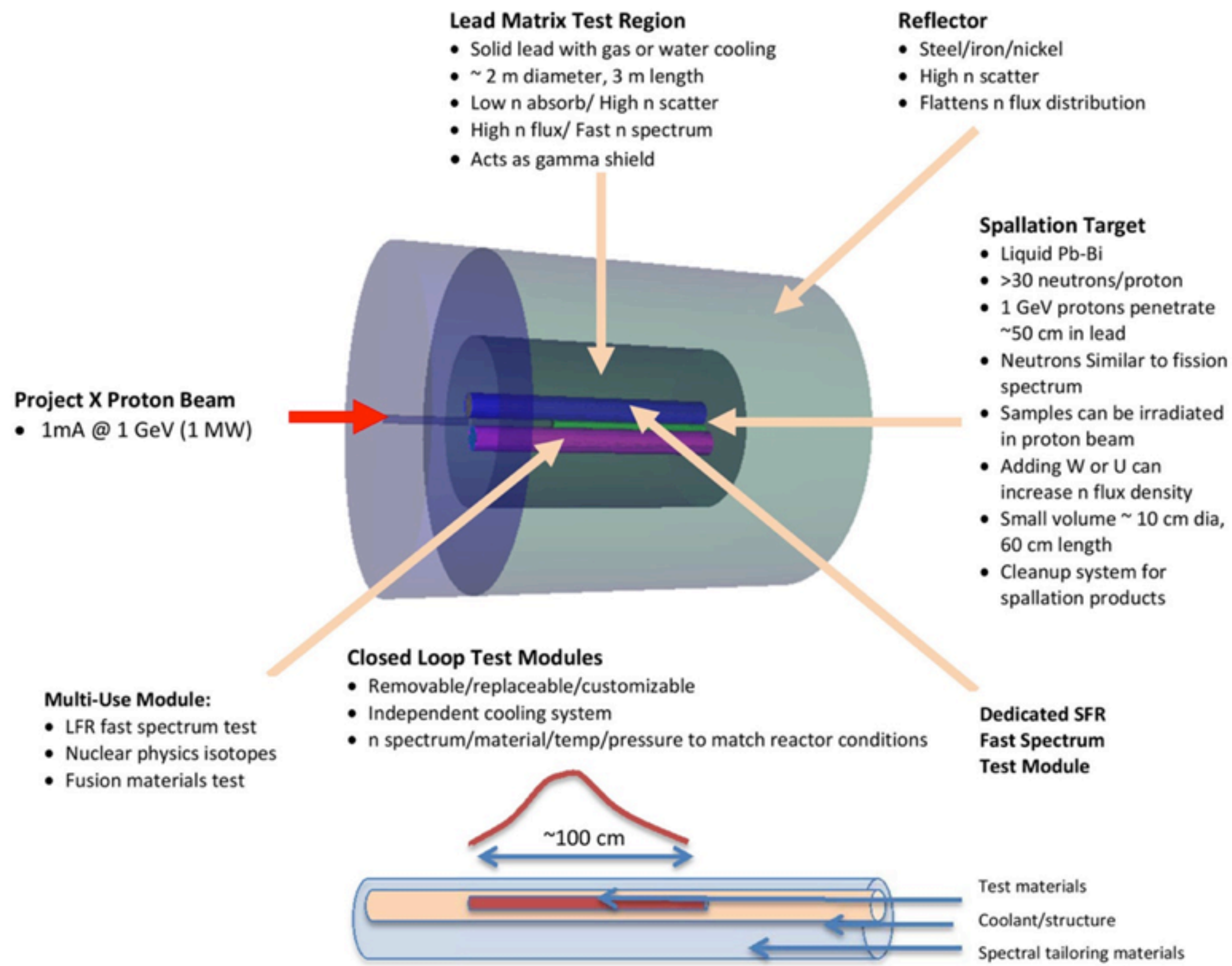


Figure 10: $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ *versus* $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ *for* $M_{Z'} = 1$ *TeV (upper panels,* C_1*: cyan,* C_2*: pink.) and* $M_{Z'} = 5$ *TeV (cyan), 10 TeV (blue) and 30 TeV (purple) (lower panels) in LHS1 (left) and LHS2 (right). Black regions are excluded by the upper bound* $\mathcal{B}(K_L \to \mu^+\mu^-) \leq 2.5 \cdot 10^{-9}$*. Red point: SM central value. Gray region: experimental range of* $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$*.*

Spallation Target for Fundamental Physics

- SNS (ESS) is (may be) oversubscribed.
- Fundamental physics waits for other disciplines.
- Aim would be to design a target optimized for EDMs (Ra, Rn, Fr), (u)cold *n*, energy applications.



EDM Sensitivities

- SM predictions and current and expected limits on selected examples of EDMs.

EDMs	SM ($\sin\delta_{\mathrm{KM}}$)	current limit	Stage 1 Project X
muon	$\sim 10^{-35}$ e cm	1.1×10^{-19} e cm	$\sim 10^{-23}$ e cm
neutron	$\sim 10^{-31}$ e cm	2.9×10^{-26} e cm	$\sim 10^{-29}$ e cm
proton	$\sim 10^{-31}$ e cm	6.5×10^{-23} e cm	$\sim 10^{-29}$ e cm
nuclei	$\sim 10^{-33}$ e cm (^{199}Hg)	3.1×10^{-29} e cm (^{199}Hg)	$\sim 10^{-29}$ e cm (^{225}Ra)
electron	$\sim 10^{-38}$ e cm	0.9×10^{-28} e cm (ThO)	$\sim 10^{-30}$ e cm (^{211}Fr)

- Probe 2–6 orders of magnitude: opportunities for transformative discoveries.

- More info: *Project X Forum on Spallation Sources for Particle Physics*.

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Lattice-QCD Laundry List

see *Lattice QCD at the Intensity Frontier*

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- Nucleon matrix elements (in OK shape and will rapidly improve):
  - sigma terms for Mu2e (same as needed for dark matter): 10–20% by 2018;
  - slope of axial-vector form factor $F_A(q^2)$ for LBNE (*cf*. eN scattering): 5–10% by 2018.
- New Muon g–2: main SM errors: HVP (dominant but firm), HLbL (subdominant but squishy).
  - General success of—and specific work from—lattice QCD makes clear than it will speak to HVP tension and eventually surpass the other methods. Spacelike vs. timelike.
  - HLbL is much more difficult: still at the idea (theory) and R&D (computing) stage.
    - several groups engaged in simpler calculations that could shed light on model estimates of HLbL, e.g., $\pi\gamma\gamma$ vertex, related to Primakoff-effect experiments.

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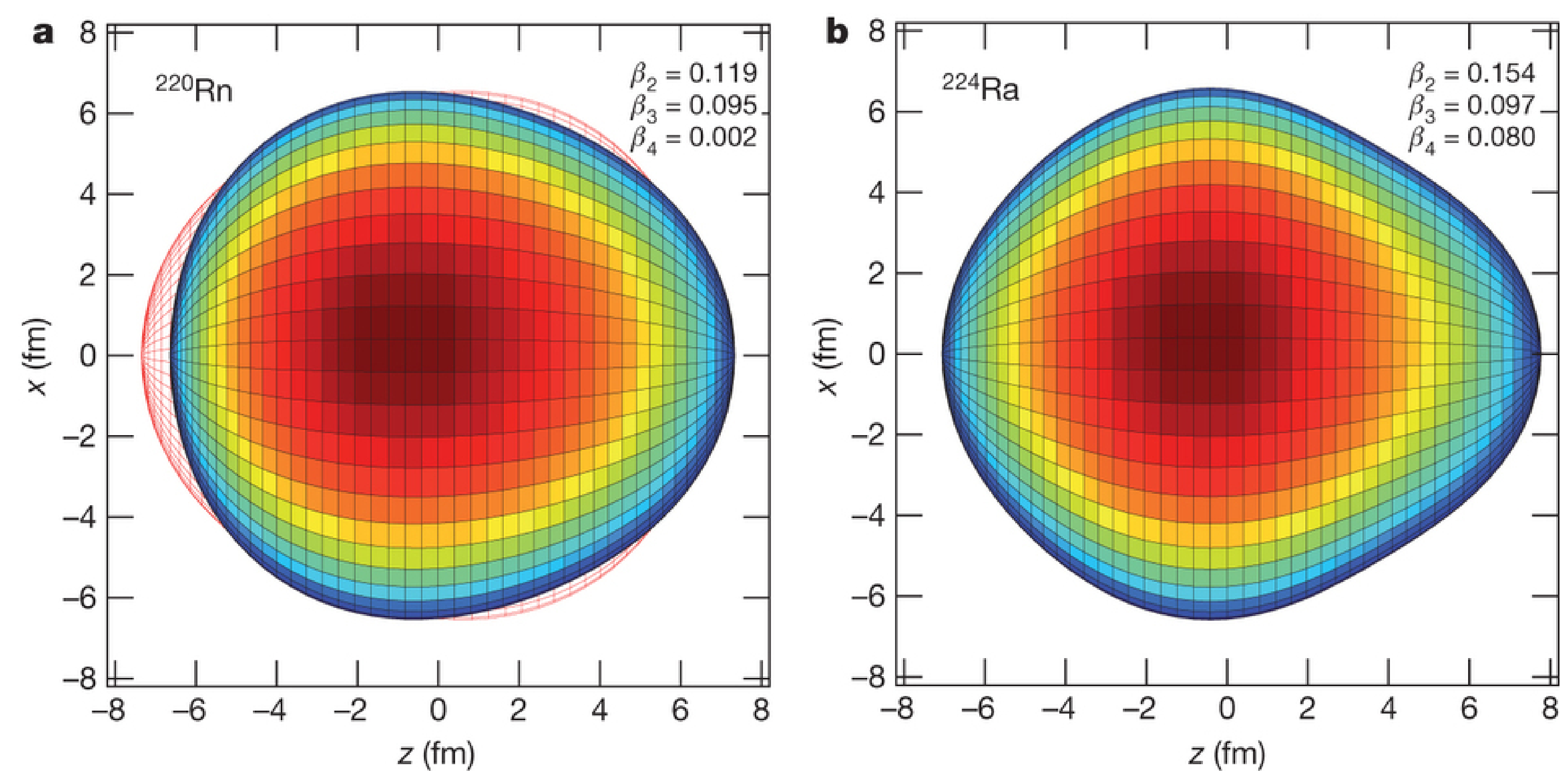
Other Possibilities with PIP^{n} Intensity

- SBL neutrino research: νSTORM is a muon storage ring to study sterile neutrinos, ….
- CLFV processes: $\mu \to e\gamma$, $\mu \to eee$, muonium-antimuonium oscillations.
- Muon magnetic moment with μ^- instead of μ^+.
- Electric dipole moments with
  - p, or even μ, in a storage ring;
  - n, ^{225}Ra, ^{223}Rn, ^{211}Fr from a spallation target—octupole enhancement.



- Neutron-antineutron oscillations: NNbarX.
- First plank in a platform for neutrino factory (NuMaX), muon collider, even VLHC.

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Flavor and Textures

The Pattern of FCNC

- Neutral flavor-changing rates take the form:

$$\Gamma = \frac{\text{couplings}}{\text{high-energy scales}} \times \text{texture} < \text{expt sensitivity}$$

where texture refers to quark masses, mixing angles, loop suppression.

- In the SM, the first factor is v^{-2}, and the texture brings in the Yukawa matrices, *i.e.*, quark or lepton masses, CKM or PMNS, and GIM.

- We do not understand where these textures come from, and no solid principle says that BSM physics should retain the SM's textures.

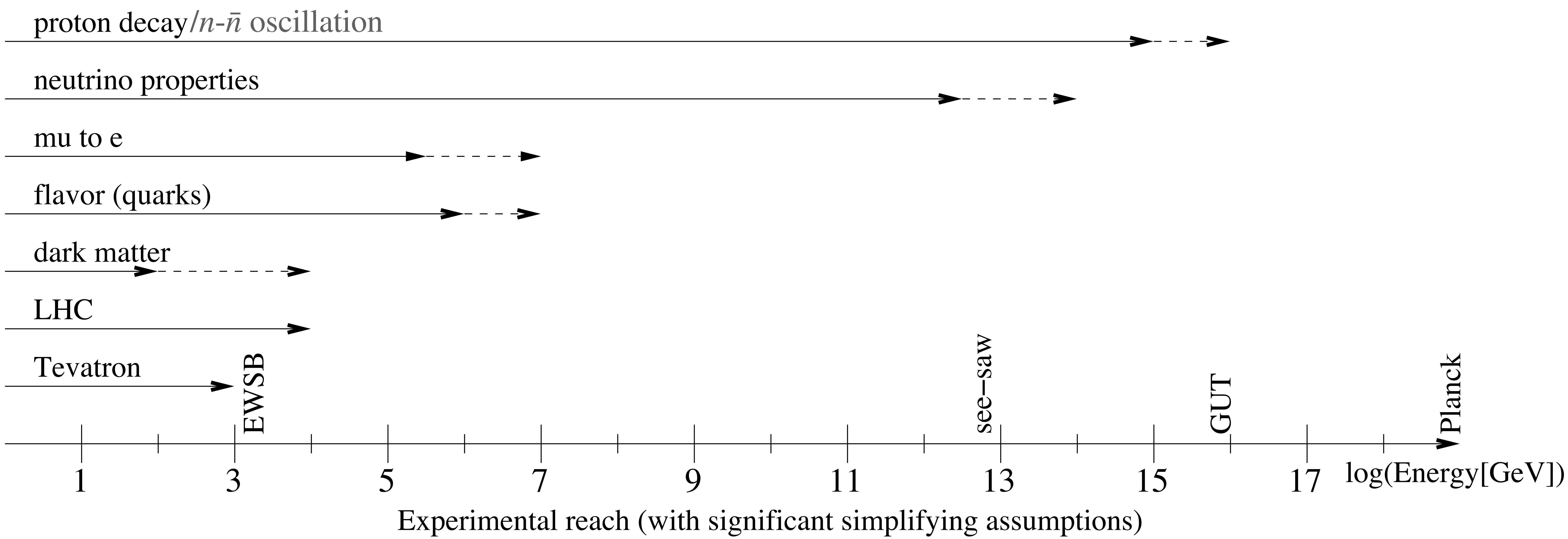
- Generically, a boring O(1) texture implies FCNC reach to *very* high energies. Conversely, (still unseen) physics at the TeV-scale would require a nontrivial texture to comply with flavor physics.

CKM

PMNS

Which path does Nature take?

- Suppose texture is boring (the *Zoltan* plot, taken from the <u>*Grossman* talk</u>):



- Alternatively, if LHC reveals rich TeV-scale physics, the BSM texture must be complicated; intensity-frontier experiments aid LHC measurements of BRs to complete the dossier.

- Not all operators are interesting (in foreseeable future):
    - *e.g.*, $\bar{b}b\bar{c}c$ operators will have small effects on ψ-Υ mixing and double B_c production.
- Phenomenologists have identified a dozen or so processes as especially promising:
    - the standard $C_{\mathcal{O}}$ vanishes or is very highly suppressed (symmetry; CKM, loops, GIM);
    - the standard $C_{\mathcal{O}}$ and matrix element (e.g., $\langle\pi|\mathcal{O}|K\rangle$) can be computed precisely;
    - the BSM $G_{\mathcal{O}}$ is expected to be large (i.e., is so in beloved models).
- Every TeV-scale Lagrangian leaves a different footprint on the $G_{\mathcal{O}}$, with details depending on the BSM couplings and masses.

- The standard $C_{\mathcal{O}}$ vanishes or is very highly suppressed:
  - the case for searches is as strong as ever, because then, if the experiment is sensitive enough, the reach is to scales higher than those probed by the LHC.
- The standard $C_{\mathcal{O}}$ can be computed precisely:
  - if not yet measured at the SM rate, the process could sensitive to post-LHC scales or even LHC physics that is hard to observe (even if produced).
- The BSM $G_{\mathcal{O}}$ is expected to be large (i.e., not much much smaller than $G_F C_{\mathcal{O}}$):
  - even with a measurement at SM rate, we are not done, because the equality of rates does not imply the equality of amplitudes.

- CP violating coupling lead to complex Wilson coefficients. Even in a process mediated by one operator, if $C_{\mathcal{O}}$ and $G_{\mathcal{O}}$ have a relative phase, it could be that

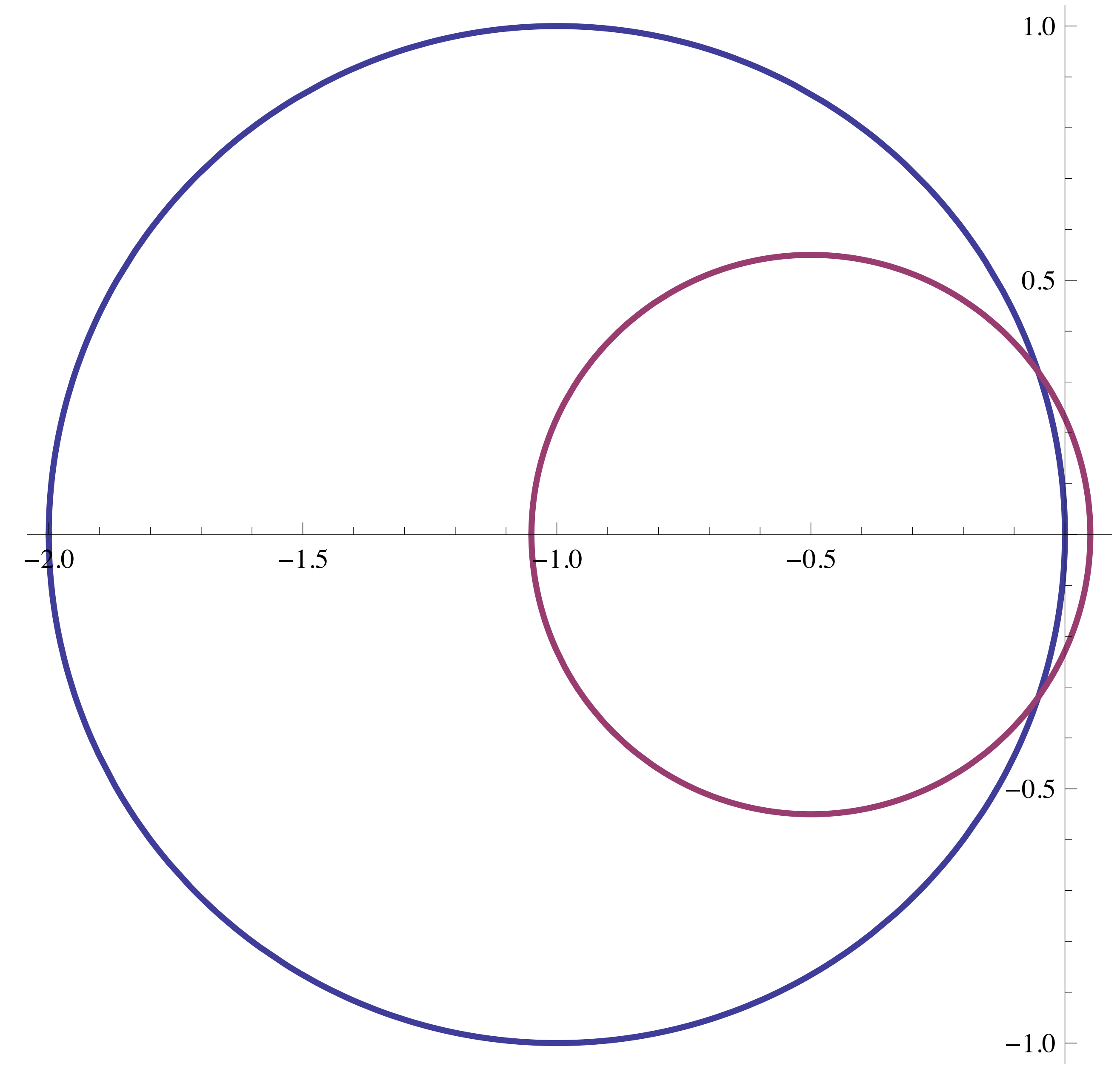
$$|G_F C_O + G_O|^2 = |G_F C_O|^2$$

- If more than one operator mediates, as in neutral-meson mixing or $B_s \to \mu\mu$, the sum of amplitudes could again add in the complex plane and preserve the SM rate (within errors).

- Simple case: two measurements probing the same physics, one of which agrees with the SM, and the other deviates. Each yields a circular constraint on the BSM amplitude.

- General case more complicated, but the lesson remains the same: one measurement is not enough.

constraints on BSM amplitude



Intersection determines the BSM amplitude (here with two-fold ambiguity).

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